Approaches to comparison of Einstein Telescope - L-shaped vs. triangle

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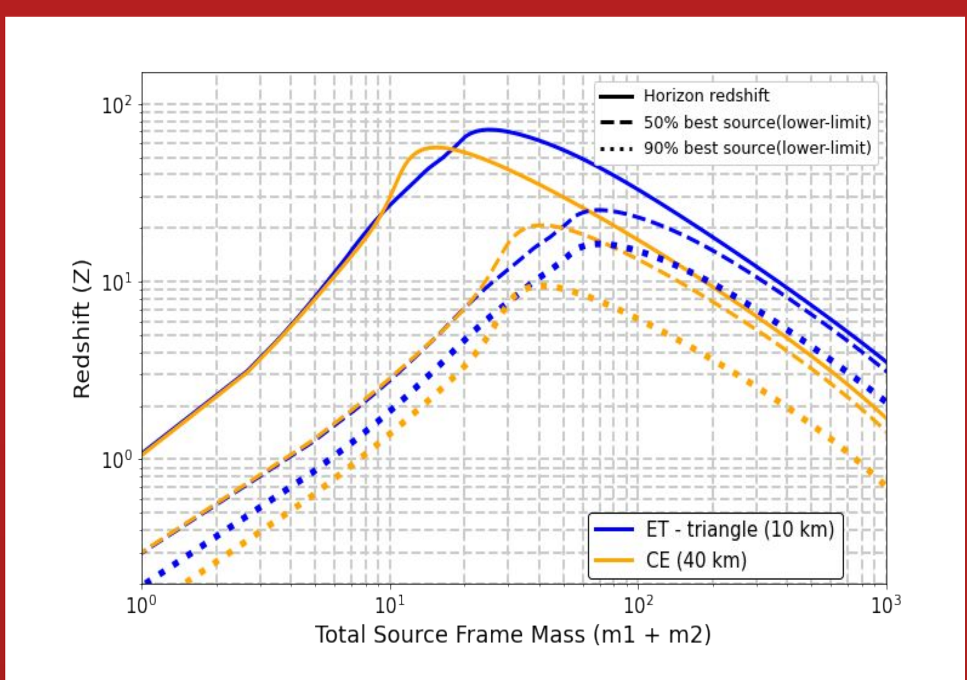
Abstract

The decision between two distinct topologies for the Einstein Telescope is imminent. One option is the proposed triangular configuration, while the other is the L-shaped configuration. The triangular setup comprises three detectors arranged in an equilateral triangle with a 60° opening angle. For the L-shaped configuration, we consider a single detector with a 90° opening angle and varying arm lengths. Our evaluation of these topologies focuses on three figures of merit: horizon plots, sky localization benefits within the network featuring Cosmic Explorer, and the utilization of the null-stream for self-calibration in the triangular configuration. In a triangular ET, the GW signal cancels when summing the output of three detectors, leaving only noise, known as the null stream. We show that the null stream can be applied to improve the calibration of the Einstein Telescope.

Redshift horizon - triangular vs. L shaped detector

The response of a gravitational wave detector is intricately linked to the location of the source in space. Even for the same source emitting gravitational waves, the detector output can vary significantly based on its position relative to the detector. To account for this dependency, we consider the isotropic distribution of sources across the sky and analyze the maximum reach redshifts achieved by 3G detectors for equal-mass, non-spinning binary systems. Solid lines indicate the horizon-redshift, while dashed and dotted curves represent lower limits of the redshift for 50% and 90% of sources, respectively.



The triangular detector configuration outperforms the L-shaped detector in achievable average redshift, leveraging its network of three detectors to enhance response by 50% and eliminate blind spots or zero-response areas.

Sky resolution of the network of 3G GW detectors

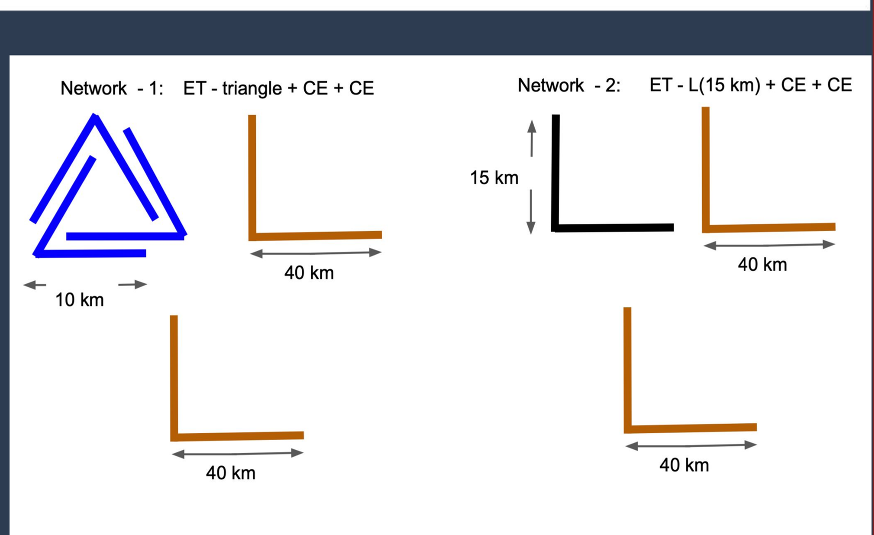
Consider the GW signal generated from equal mass compact binary system

↓

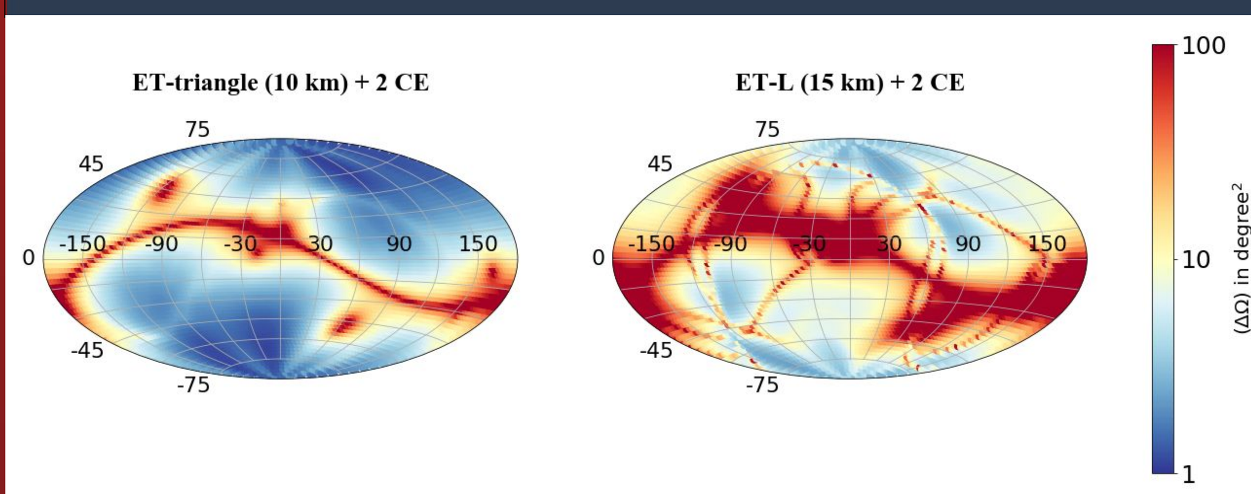
GW source placed uniformly across the sky

↓

Calculate angular resolution for each sky position for both detector network configurations



Network 1: ET- triangle + CE + CE
Network 2: ET- L shaped + CE + CE

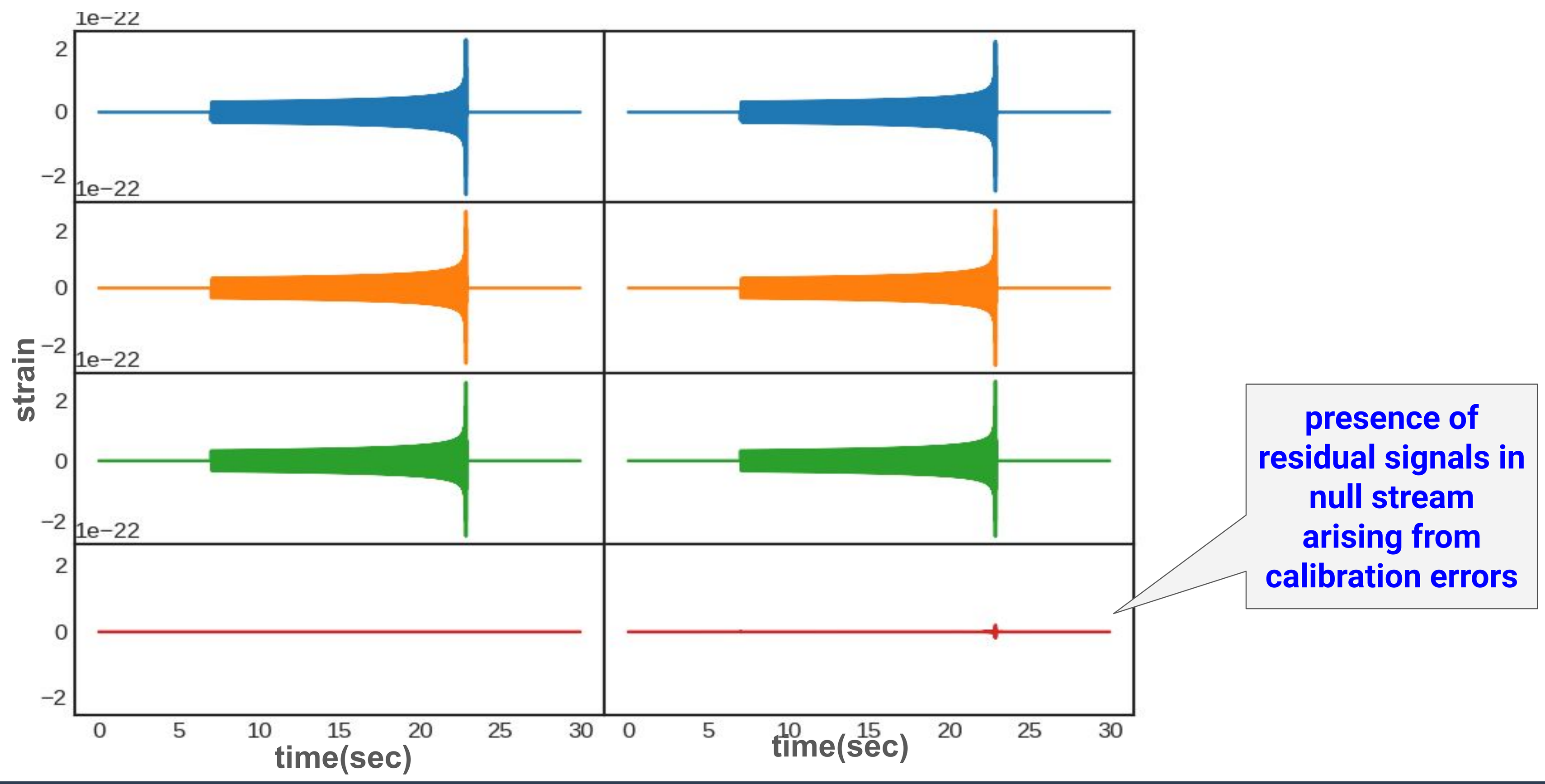


Sky localisation error	ET -Triangle + 2 CE	ET- L (15 km) +2 CE
< 10 deg^2	56 %	40%
< 20 deg^2	66%	58%
< 30 deg^2	77%	65%

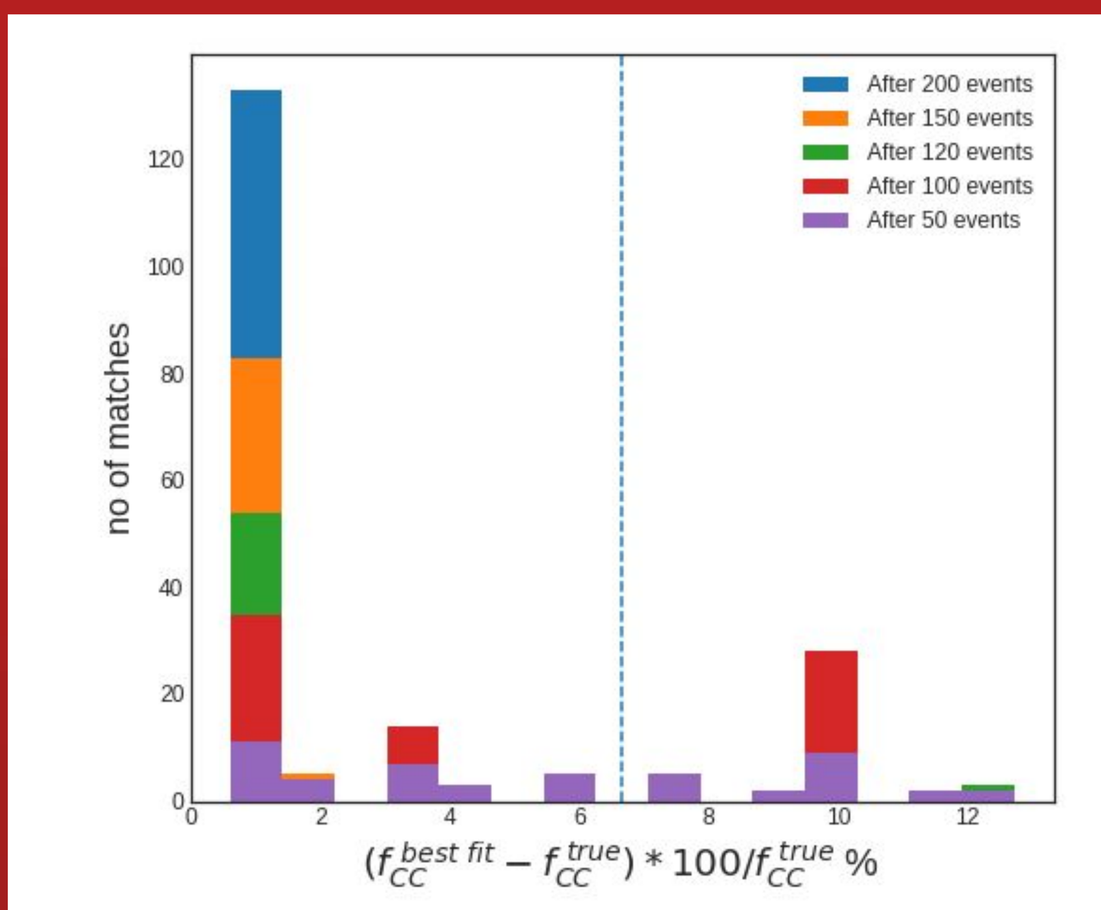
Figure shows the directional precision of the detector network for unmodeled GW signals, with each point indicating the error in sky localization for sources arriving from the corresponding direction. ET-Triangular configuration outperforms ET-'L' shape (15 km) with 2 CE detectors.

Enhancing Detector Calibration through the Application of Null Stream of ET-Triangle

The "null stream" is a unique data stream formed by summing the strain outputs of the constituent interferometers within the triangular design of the Einstein Telescope. This data stream is typically signal-free when the detector data is accurately calibrated. However, errors in modeling the detector output can lead to calibration inaccuracies. Consequently, residual signals may persist in the null stream, as illustrated below.



Since the signal-to-noise ratio of the residual signal is typically very small, it cannot be reliably detected with a single GW event. However, by combining the residual signals from multiple events detected within certain time periods, assuming the detector response remains relatively stable, we can enhance our ability to detect and analyze these small signals. The figure below illustrates how increasing the number of events combined allows for a reduction in calibration parameter errors (along the x-axis).



The peak of the histogram signifies a reduction in calibration error, with the percentage error along the x-axis approaching zero. As we combine more and more events to calculate the cumulative signal-to-noise ratio of the residual signal in the null stream, the peak value increases.

Conclusion

- **The maximum attainable redshift is higher for the triangular detector, considering all sky directions.**
- **Sky localization accuracy is better for ET-triangle compared to ET-L shape detector in third-generation detector networks like Cosmic Explorer.**
- **ET-triangle offers an advantage with its null stream, aiding in improving calibration accuracy for all three detectors in the ET network.**

References:

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[3] Singha, Ayatri. "Gravitational wave astronomy with current and future generation detectors." (2024).